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Art. IV.—*The Geology of Bindi, Victoria.*

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Abstract.

South of Mt. Tambo, Middle Devonian limestones unconformably overlie metamorphic schists and gneissic granite. The granite is intrusive into sandstones, presumed to be of Upper Ordovician age. A flow of rhyo-dacite overlies the schist complex, and is conformably overlain by the Middle Devonian limestones. Petrographically the flow is identical with flows at Buchan, classed with the "Snowy River Porphyries".

The structure of the limestones is a westward-dipping monocline of variable dip, which has been faulted into its present position, with the development of an extensive shear zone along its north-eastern boundary. Upper Devonian conglomerates overlie the limestones, with no evidence of a major angular unconformity. The conglomerates have been involved in the shearing processes, with the limestones.

Introduction.

The area dealt with in this paper comprises the major portion of the Parish of Bindi, together with portions of the surrounding parishes of Moonip, Eucambene, Terlite-Munjie and Ensay. The approximate boundaries are: to the north and west, the Tambo River; to the east, the Nuniyong Plateau; and to the south, Junction Creek and the ranges west of Mount Bindi. Access to the parish is gained by a single track from Tongio, which is on the Omeo Highway, about 60 miles north of Bairnsdale.

The earliest published reference to the area is that of A. R. C. Selwyn (1866) in which he suggests that the Bindi limestones overlie the "plant-bearing sandstones and conglomerates" of

Mount Tambo. The age of the limestones was shortly afterwards established as Middle Devonian by McCoy, who in 1876 listed the fossils then known.

A. W. Howitt, in his classic paper on the Devonian rocks of North Gippsland, produced evidence to show that the limestones underlie the Mount Tambo beds and overlie the quartz porphyry and gneissic granite. He also showed that the Tambo beds were not metamorphosed to the same extent as the Upper Ordovician, attributing the changes produced in the Tambo beds near their contact with the granite, to percolation of siliceous solutions along this plane of weakness. Although he found westerly dips to prevail throughout the limestones, he postulated a synclinal attitude for these beds, regarding them as having been deposited on a granite-quartz porphyry basement complex, and subsequently undergoing open folding and erosion. Their denuded remnants were then covered by the Tambo beds.

J. Stirling (1884) noted the occurrence of marble at Bindi, and assigned its origin to the contact metamorphic effect produced in the Middle Devonian limestones by the quartz porphyry, which he considered to be intrusive. In the bed of Old Hut Creek, he recorded "protruding blocks of purplish and brownish conglomerate, the dip being rather obscure." Since these blocks were at a lower level than the limestone outcrops, he considered that they, and the analogous Tambo beds, underlay the Middle Devonian. It can now be shown, however, that this apparent discrepancy is due to faulting. In a later paper (1886) he developed his idea, mapping a coarse reddish conglomerate as extending underneath the Bindi limestones and outcropping along most of their eastern boundary. During 1886, however, he worked in collaboration with Howitt, and they concluded that the porphyry was not intrusive, the marmorisation being due to the pressure exerted on the limestone by a once considerable thickness of overlying rocks. Howitt also showed that the evidence given by Stirling regarding the Lower Devonian age of the Mount Tambo beds was inconclusive. In a report on a survey of the parish of Bindi, O. A. L. Whitelaw lists and briefly describes the various formations. His summary of the history of the area in no way differs from that given by Howitt.

Physiography.

The Bindi limestones lie in a topographic basin, bounded on all sides by steep ridges of harder rocks. The limestones have been let down into their present position by faulting, and, owing to their greater susceptibility to erosion, the area in which they occur has been reduced in level below that of the surrounding ranges.

In the northern part of the area, the Tambo River flows westward, skirting the edges of the massive conglomerates and sandstones of Mount Tambo, and forming the northern boundary of the parish of Bindi. Just before reaching the granite, the river swings in a right-angle bend, and flows southwards through a zone of fractured gneissic rock which extends parallel to the old fault line determining the western boundary of the limestone. In this part of its course, the river is joined by three tributaries—Old Paddock Creek, Bindi Creek and Junction Creek. Old Paddock Creek drains the acid lava flows covering the eastern portion of the parish of Bindi and the lower ridges of the Nuniyong Plateau. In its upper course, this creek flows north-west, following the strike of the limestones along their eastern escarpment, and then cuts through the limestone escarpment to flow westward through less resistant shaly limestones. Bindi Creek flows north-west through the centre of the area, draining the dip slopes of the limestones. Junction Creek marks the southern boundary of the basin. It rises on the western slopes of Mount Bindi and flows westward over the metamorphic rocks of this part of the area.

The greater part of the limestone is covered with a thick mantle of reddish soil, and is almost treeless, the rounded grassy slopes contrasting sharply with the forests and rugged peaks of the surrounding ranges, many parts of which are so precipitous as to be almost inaccessible. With the exception of a sheep station and one or two small farms along Bindi Creek, the district is uninhabited, the only part which has been surveyed by the Lands Department being the limestone area contained within the parish of Bindi.

The Metamorphic Complex.

The basement complex of the Bindi area comprises rocks typical of the Metamorphic Complex of north-east Victoria. The eastern portion of the parish of Bindi is composed of regionally metamorphosed sillimanite-garnet-mica schists and gneisses, comparable with the rocks described by Howitt (1888) in the "Omeo Series," and later described as regionally metamorphosed Upper Ordovician sediments by Tattam (1929). In the western portion of the parish a gneissic granite is intrusive into acutely folded sandstones and shales, which show no trace of regional metamorphism. They are, however, lithologically identical with the series extending to the south of Bindi, which is mapped as Upper Ordovician by the Geological Survey The occurrence of such widely different metamorphic types within the parish of Bindi could be due either to extensive faulting or to a stratigraphical unconformity between the regionally metamorphosed series and the almost unaltered sandstones and shales. The sharp line of junction between the two formations seen at Junction Creek and the absence of basal conglomerate in the sandstone-shale series suggests that faulting has been the more probable mechanism. In the regions to the south and south-west of Bindi, the Palaeozoic formations are similar in most respects to the rocks of the Junction Creek area, generally comprising indurated and silicified sandstones. The boundary line separating these types from the regionally metamorphosed Omeo series is defined by a system of faults, one of which strikes N.,N.W. through the Bindi area. A similar abrupt junction to that at Junction Creek occurs at Tongio Gap, where Howitt (1888) describes a major fault striking N.W. and persisting for many miles.

Schists and Gneisses of the Omeo Series.

Howitt originally divided this series into two main groups of rock types:

(i) Schists and phyllites resulting from the alteration of a series of Upper Ordovician sediments.

(ii) Gneisses and schists produced by the effect of pressure metamorphism on the intruding granites, i.e., ortho-gneisses.

Both groups are present in the portion of the complex exposed on the western and northern slopes of Mount Bindi. Owing to the inaccessibility of the country, little is yet known regarding the relative positions of the bands of sillimanite schist and gneiss, graphitic schist, and biotite schist which make up this region. The various bands of schist and gneiss alternate rapidly, reflecting the original compositions of the sediments, which can be inferred to have comprised sandstones, aluminous shales, carbonaceous sandstones, and types intermediate between these. The general strike of the beds is slightly to the west of north, dips generally being erratic, but always at high angles. Lustrous, fine-grained, sillimanite schists are well developed along the southern bank of Junction Creek, immediately south of the limestone termination, and east of the extension of the line of faulting which determines the western boundary of the limestone. West of this line of faulting, the schists are absent, their place being taken by granite and indurated sandstone.

Upper Ordovician.

The ridges of indurated sandstone and shale occupying the south-west corner of the parish of Bindi represent the north-eastern boundary of the sandstones typical of the Swift's Creek district. In the lack of palaeontological evidence they are provisionally regarded as belonging to the lithologically similar Upper Ordovician formations of north-east Victoria. Although indurated and disrupted by a local granitic intrusion, they show no trace of the intense metamorphism which has affected the (?) Upper Ordovician rocks in the eastern portion of the parish. The granite causing the contact metamorphism of the sediments is typical of the plutonic rocks of the metamorphic complex of north-east Victoria, showing petrographic similarity with both the gneissic granites of Omeo and the more normal granites of Ensay, to the south of Bindi. Movement along flow planes during the later stages of intrusion, coupled with the development of cataclastic structures by movement along shear planes subsequent to consolidation, has given the rock a foliated appearance, which is more strongly marked in the outcrops near Junction Creek, where the rock grades into an ortho-gneiss.

It is probable that a small area of sericite-chlorite schist on the northern slopes of Cairn Hill belongs here, since it shows little affinity to the rest of the Omeo schists. It probably represents a small roof pendant of Upper Ordovician, similar to those found to the west across the Tambo. Field relations at this point are rendered obscure by the presence of a number of massive quartz veins between the schist and the limestones. Mineralised fissures in the quartz contain chalcopyrite, azurite, and small amounts of gold and silver.

Acid Extrusives.

Along their eastern boundary, the Bindi limestones rest partly on metamorphic rocks, and partly on an acid lava flow which occupies the north-eastern portion of the parish and the areas to the north, on the east side of Mount Tambo. This flow was included by Howitt (1876) in the extensive series of eruptives and pyro-clastics forming the "Snowy River Porphyries." Stirling, however, later (1886) described the flow at Bindi as distinct from the main mass of L. Devonian eruptives in eastern Victoria. The present work confirms Howitt's views, correlating the flow at Bindi with petrographically similar types at Mt. Cobberas, Wombargo, and Murrendel. Tuffaceous phases occurring at Bindi show the characteristic features of the fragmental rocks common in the "Snowy River Porphyry" complex. These tuffs are well exposed along the southern limits of the lava flow, comprising several varieties intermediate between massive red lavas and silicified white tuffs streaked and spotted with purple and red material. The similarity of this rock in the field to the conglomerates of Mount Tambo seems to have given rise to Stirling's misconception as to the "Lower" Devonian age of the latter series. The tuffaceous material definitely underlies the Middle Devonian, but, when sectioned, bears no resemblance to a true conglomerate.

A petrographic examination of the massive lava (see p. 23) shows that the rock is of the rhyo-dacite type, corresponding to dellenite as described by Brögger. The toscanites and quartz-latites approach the dellenites in composition, but are to be distinguished therefrom by slight differences in the composition of the plagioclase and the amount of quartz present, respectively. Considering the similarity between the flow at Bindi and other flows scattered throughout the Snowy River volcanic complex, it is expected that the bulk of the complex will eventually be shown to be composed of true "volcanic" rocks, so that the term "Snowy River Porphyries" should at present be replaced by the more noncommittal term "Snowy River Series." Such a series could be understood to include rhyo-dacites, pyroclastics and tuffaceous extrusives, as well as true hypabyssal porphyries and porphyrites, if the existence of such can be established. Skeats (1909) suggested that some of the more fluidal types should be termed rhyolites. Evidence is now pointing to the term "rhyo-dacite" as a useful general, though fairly exact, description of most of the rocks comprised in the "Snowy River Complex."

Bindi Limestones.

NORMAL LIMESTONES.

The "Bindi limestones" consist of shallow-water marine limestones and calcareous shales, which have been shown on palaeontological grounds to be of Middle Devonian age. (Howitt, 1876; McCoy, 1877). The beds have been regarded as having originated under shallow water conditions in a small marine basin, isolated from the main sea in which the more extensive limestone deposits of the Buchan district were being formed. (Howitt, 1876; Whitelaw, 1898). However, the present boundaries of the limestones are not those defined by the limits of sedimentation in the original sea or estuary, but are largely fault boundaries. It is thus inferred that the Devonian limestones and conglomerates in this area once formed part of more extensive formations, the bulk of which has been removed by erosion. The existing remnants at Bindi have been preserved by down faulting. Howitt (1878) described similar extensive faults along the edges of the limestones at Buchan and Murrendel.

Lithology.—The limestones occupying the central areas of the tilted fault block have entirely escaped cataclastic disruption, whilst near the eastern edge of the fault block extreme deformation indicates the extent of the faulting. These latter features of deformation will be described below in the section on marmorised limestones. The normal limestone beds in the central areas show few signs of shattering or flexure, and preserve their original relations to one another. These beds comprise massive blue-grey limestones, with minor amounts of impure thin-bedded limestones. The thick massive limestones are rich in stromatoporoids and corrals, whilst the thin argillaceous beds are crowded with brachiopods. Along the north-eastern boundary a few outcrops of fine sandstone and shale are exposed.

Along Old Paddock Creek, black calcareous shales are interbedded with thin discontinuous bands of massive, sparsely fossiliferous, limestone. The alternation of shale and limestone is fairly regular, the distance between any two bands of limestone rarely exceeding 6 in. The conditions under which such a deposit could form would probably occur in a marine environment subject to a seasonal influx of water charged with fine silt. The presence of such argillaceous material in quantity would render impossible the growth of the fossils which usually characterize limestone deposits; thus it is found that the shale is completely unfossiliferous, whilst the recognizable forms in the limestone bands are both stunted and rare.

In general, the thick beds of "stromatoporoid" limestones are the purest in the area, and correspond closely with the normal Buchan limestones in lithology. Thinly laminated argillaceous limestones with innumerable brachiopods are widespread in the Bindi area, and are usually rich in both carbonaceous and sulphur-bearing impurities. The white chalky limestone mentioned by Whitelaw (1898) is a secondary deposit, similar in some respects to travertine. It is friable in texture, often with a "honey-comb" surface structure, and is most abundant on the dip slopes of the limestones.

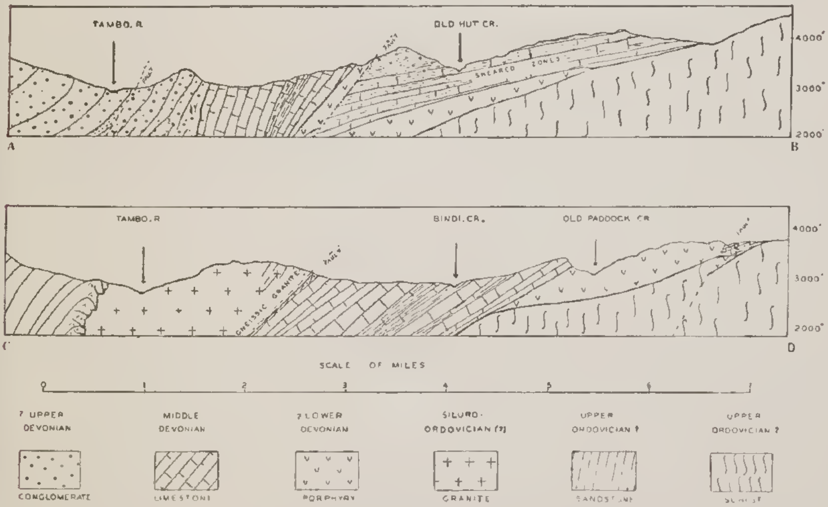

FIG. 1.—Diagrammatic sections across the Bindi Limestones from A to B and from C to D on the geological sketch. Contours are approximate and vertical scale 1 inch = 4,000 feet.

Field Relations.—The whole of the unaltered limestones occupying the central area of the parish of Bindi appear to be contained in one single block, which has undergone tilting in a westerly direction combined with slight torsional flexing, giving gradually increasing dips as the northern boundaries are approached. Dips in the southern portion of the area range from 15°W. to 30°W., whilst in the northern half of the area the range is from 50°W. to 80°W.

A continuous series of dips can be observed along Old Paddock Creek, where a traverse from west to east suggests that the major structure has originally been a broad, open, monoclinal fold of limestone, the western edge of which has been faulted into contact with the granite, whilst the eastern extension of the fold has been removed by erosion. The area of limestone further to the east seems to represent a down-faulted block which possibly formed the footwall of an extensive thrust fault, shearing along which has caused intensive distortion of the limestone and the Tambo conglomerates which here overlie them (see " Marmorised Phases "). Thus it is found that dips at the contact of the limestones with the granite are from 60°W. to 80°W., i.e., the beds dip into the granite at a high angle. Proceeding eastwards, the inclination of the beds gradually decreases, until on their eastern boundary they become horizontal, then, over a small area north of Old Hut Creek, they dip eastwards at about 30°. This is probably due to drag associated with the subsidence of the north-eastern block. The limestones cannot be traced any further eastward owing to the sudden appearance of sheared and distorted purple conglomerates belonging to the Mount Tambo series.

An alternative view could be advanced regarding the structure of the limestones, whereby the beds are overfolded along a north-south axis, to form an acute asymmetric syncline with its axial line crossing Old Paddock Creek at a point about 600 yards east of the limestone-granite contact. The fact that no such axis could be detected in the beds along Old Paddock Creek discredits this synclinal hypothesis. Since the whole of the limestone outcrops across the area appear to represent beds conformable to one another, the total thickness of limestone and calcareous shale in the series is of the order of 3,000 ft.

The eastern boundary of the limestones is an erosion escarpment up to 200 ft. in height, which forms cliffs along the upper portions of Old Paddock Creek and Bindi Creek. Definite evidence that the beds were originally continued on towards the east, over the rhyo-dacite core of the fold, is provided by the occurrence of sheared and " stretched " marmorised limestones for some miles beyond the eastern boundary of the normal limestones. The significance of this occurrence has been apparently overlooked by Howitt and Whitelaw. Although Stirling (1884) recognized the northern limit of the zone, he did not attempt to explain the intensely sheared rock types.

Although earlier reports of Stirling and Howitt mention basal conglomerates in the Bindi limestones, which they emphasized as confirming the basin-deposition theory, no such basal conglomerates could be found along either the eastern or western

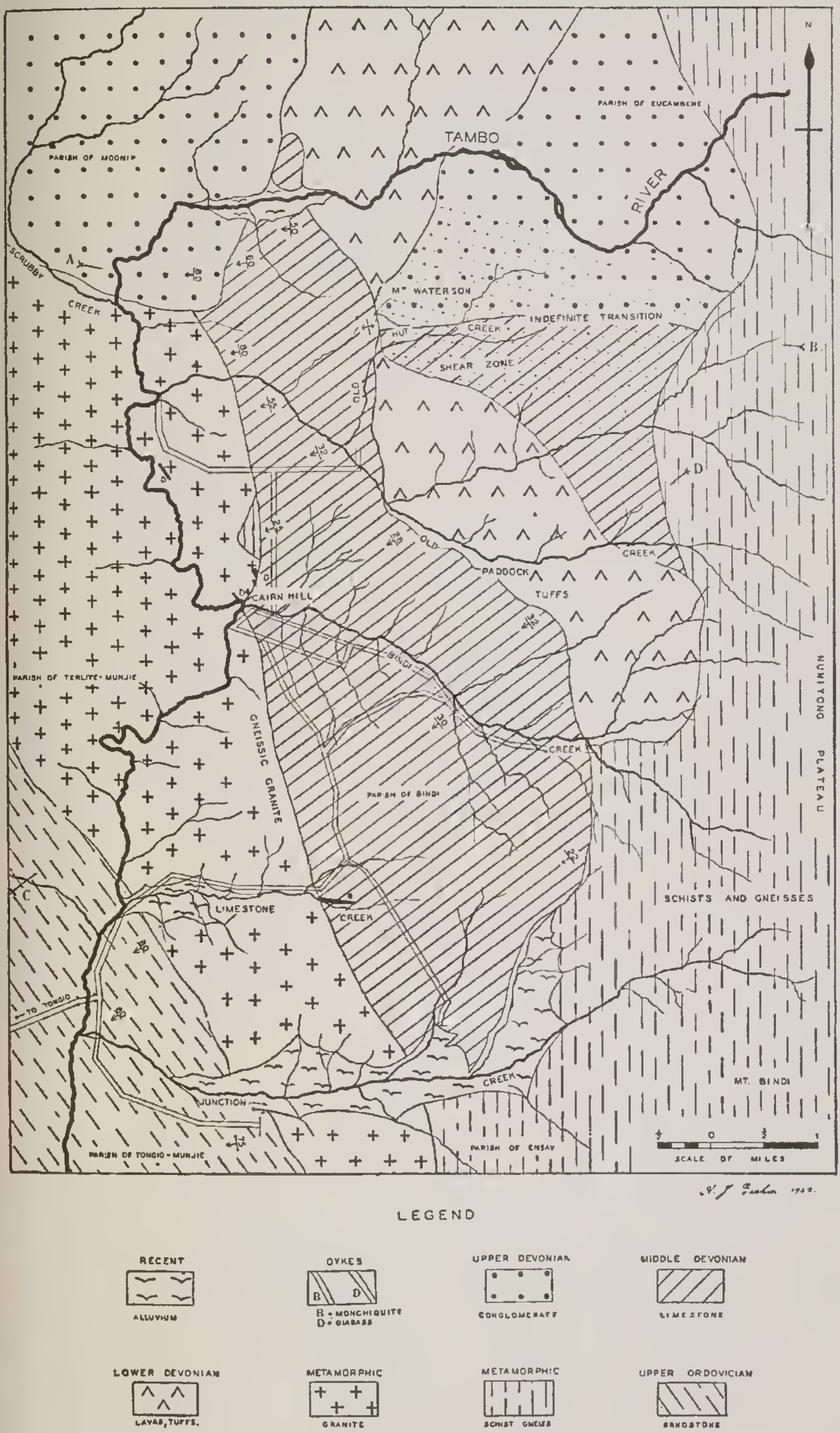

Fig. 2.—Geological Sketch Map of the Bindi Area.

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boundaries of the limestones. The basal beds of the limestone series are well exposed in the cliffs of the erosion escarpment, and everywhere it was noted that the basal beds were massive and shaly limestones exactly corresponding to the beds occurring higher up in the series. These calcareous beds rest directly on either the rhyo-dacite, its tuff phases (which strongly resemble conglomerates in the hand specimen), or the metamorphic rocks in the southern corner of the area. The supposed "basal conglomerates" may be identified with the uppermost "tuff" bands of the lavas.

In the extreme south of the parish, the limestones disappear at Junction Creek, without any apparent lithological or structural changes having taken place, and are replaced on the southern bank of the creek by precipitous cliffs of Upper Ordovician shales and sandstones to the west, and to east the metamorphic granite and schist of Mount Bindi.

To the north, the limestones pass under the conglomerates and sandstones of Mount Tambo. The two formations have strikingly similar attitudes, the extreme angular unconformity noted at Tabberabbera between Middle Devonian limestones and shales and Upper Devonian sandstones and conglomerates (Skeats, 1929) being absent. The southern extremity of the Mount Tambo beds overlaps the western boundary of the limestones to a slight extent, but in the field there is no indication of the mechanism by which this has been brought about. The limestones here dip at about 80°W., and, within a few yards, are abruptly replaced to the north by coarse felspathic sandstones and conglomerates of the Mount Tambo series in a massive sequence of beds striking parallel to the limestones and dipping like them at about 80°W. The north-eastern corner of the limestone area shows the beds dipping fairly steeply to the west, with a rugged erosion scarp where they have been removed from the crest of the fold, exposing once again the core of rhyo-dacite, which itself shows signs of broad folding and fracturing where it is exposed along the Tambo River.

The western boundary of the limestones is remarkable primarily for the straight-line junction between the sediments and the granitic rocks. In the field the line of junction can be traced for six miles over steep hills and down into valleys without any major deviations from a north-south line. This boundary cannot represent the boundary of a basin-like deposit, which should show an indented line of junction depending on the altitude of the surface outcrops. In addition, the limestone beds dip to the west throughout the area. A formation deposited in a marine basin, or subsequently converted into a structural basin by folding, would show beds dipping in opposite directions on either side of the area of outcrop, hence it must be assumed that the junction between the limestone and the granite at Bindi is the result of faulting along a north-south line. Abundant evidence of cataclastic disruption can be found at the fault junction. Most of the disruption has apparently taken place in the border zone of the granite, which shows considerable shearing. Fault agglomerates and slickensided surfaces are developed to some extent on the hillsides north and south of Bindi Station, but elsewhere the rock in the crush zone is sheared and broken up into a characteristic mass of fine quartz particles interspersed with biotite, chlorite, and secondary calcite. The entire absence of any traces of thermal metamorphism in the limestones shows that the granite has not intruded these beds. Intensive search failed to reveal any evidence of recrystallization or even of induration in the limestones along their western boundary.

Palaeontology.—The fossils in the limestones, though abundant and often well-preserved, are limited throughout to a few characteristic generic and specific groups. A review of the literature has shown that the following forms from Bindi have been recorded.

STROMATOPOROIDEA.—*Stromatopora concentrica* Goldfuss, 1826.
Syringopora speleana Etheridge, Jr., 1902.

PORIFERA.—*Receptaculites australis* Salter, 1859.

ANTHOZOA.—*Favosites multitabulata* Etheridge, Jr., 1899.
(*F. gothlandica* of Stirling, 1886.)
Campophyllum gregoryi Etheridge, Jr., 1892.
Cystiphyllum (?) sp.

BRACHIOPODA.—*Atrypa aspera* Davidson, 1865.
Atrypa reticularis Linnaeus, 1767.
Chonetes australis McCoy, 1876.
Spirifer yassensis De Koninck, 1877.
(*S. laevicostata* of McCoy.)
Spirifer howitti Chapman, 1903.

PELECYPODA.—*Pterinaea* sp.

CEPHALOPODA.—*Danaoceras* (?) *bindiense* Teichert 1939.
(*Phragmoceras subtrigonum* of McCoy.)
Goniatites sp. (?)

PISCES.—*Phlyctaenaspis* (?).
(*Asterolepis* of McCoy.)

Most of the forms previously recorded from Bindi were identified in the course of the present survey, although types such as the ganoid scales mentioned by Whitelaw (1898) and the Asterolepid recorded by McCoy (1877) were not observed. Fragmental forms occur which bear some resemblance to the *Phragmoceras subtrigonum* of McCoy, which has recently been re-described as a new form related to *Danaoceras* (Teichert, 1939). A thin, but well-defined band of blue limestone about 80 ft. up the cliff along the western bank of Old Paddock Creek is crowded with well-preserved casts of *Tentaculites,* closely comparable with *T. ornatus,* one or two specimens showing traces of striae between pairs of individual transverse ribs. *Leptaena* and *Orthis* are plentiful in the shaly limestones along Bindi Creek. A cast of a form strongly resembling *Cyclonema* was also found in the Bindi Creek beds. The massive limestones to the east of this locality yielded a large *Euomphalus,* and numerous sections of shells of the *Loxonema* type. Crinoid ossicles and long stems (up to 4 in.) are extremely abundant throughout the whole of the Bindi deposits, but no calices have been observed.

A comparison of the fauna with that of Buchan indicates general similarity, though the trilobites, gasteropods, and lamellibranchs found at Buchan are unknown or very rare at Bindi.

On the whole, the fossils are typically Devonian types, some such as *Spirifer yassensis* and *S. howitti* being characteristic of the Middle Devonian, whilst *Leptaena, Orthis, Chonetes* and others persist throughout both the Silurian and Devonian. An exact determination of the horizon of the deposit relative to the European series could probably be obtained by detailed examination of the Stromatoporoid or Coral faunas. Thus, if the previous identifications of *Stromatopora concentrica* are upheld, the possible age of the Bindi limestone series is restricted to the Givetian horizon of the Middle Devonian.

Marmorised Limestones.

Rocks of both the Middle Devonian limestone series and the Mount Tambo conglomerate series are exposed over an area of about 5 square miles surrounding the upper reaches of Old Hut Creek. The appearance of these rocks in the hand specimen and under the microscope indicates that they have undergone intense shearing, with consequent elongation of the various sedimentary components along the shearing planes. The dominant mechanism of elongation could have been either "stretching" of the material in the direction of movement of the sheared layers (elongation along the "A" axis of the tectonite) or elongation due to "rolling" of the material between shear surfaces with consequent extension of the grains and pebbles in a direction parallel to the intersection of complementary shear planes, but at right angles to the direction of movement (i.e., elongation by rotation about the "B" axis of the tectonite).

The first process would require extensive intergranular movement along shear planes at a low angle to the horizontal (about 25° as shown by the dip of the elongated fragments). Such movement could only have been produced by thrust faulting. In the field, the direction of slip along such a fault, as deduced from the direction of elongation of the sedimentary components, is in approximate agreement with the direction from which the compressive forces producing the granite-limestone thrust fault in the west must have acted. There is thus some reason to attribute the distortion and marmorisation of these rocks to the action of a second thrust plane extending underneath the eastern boundary of the normal limestones.

Elongation by rotation about a "B" axis would correspond in the field to the action of normal block-faulting. The shear zone in such a case would be a downthrown block, defined by a north-south fault along its western edge. It seems very improbable that block faulting could result in a shear zone of such lateral extent as that exposed in this part of the Bindi area.

Lithological Characteristics and Field Relations.—The Middle Devonian beds in the shear zone comprise massive blue limestones grading into calcareous conglomerates, the latter being in turn replaced by the siliceous conglomerates of the Mount Tambo series. This apparent gradation suggests that the time interval between the deposition of these formations was not as great as their allocation to the "Upper" and "Middle" Devonian periods would suggest. It is possible, however, that intermixing of the two formations has occurred during faulting.

At the western boundary of the shear zone, the limestones are almost normal, with abundant recognizable fossils (Plate 1, fig. 5). Proceeding eastward, however, the shear planes become more pronounced until the rock grades into a fine-grained "marmorised" type, in which the bedding planes have been almost obliterated (Plate 1, fig. 6). As far as could be determined, the pinkish iron-stained seams which represent the original bedding strike approximately north-west, dipping at 50°–55° to the south-west.

The shear planes, along which the rock cleaves readily, strike at 68°–70° west of north, dipping in a southerly direction. Towards the north, the limestones are gradually replaced by calcareous conglomerates, in which the pebbles are considerably elongated in the direction of the shear planes. The dip of the "stretched" pebbles along the direction of elongation is at a low angle to the west.

Further to the north in the shear zone, the calcareous conglomerates are themselves replaced by siliceous conglomerates, at first yellow to brown in colour, but ultimately showing the reddish-purple tints characteristic of the Mount Tambo beds.

The northern portion of the sheared area is composed entirely of these purple conglomerates, which are obviously the sheared representatives of the normal purple conglomerates exposed on the slopes further north at Mount Tambo. The strike of the shear planes in these latter conglomerates is rather different from that in the marmorised limestones, being 25 degrees west of north, whilst the dip is indeterminate owing to the massive nature of the bedding. Tension gashes are strongly developed at right-angles to the elongation of the pebbles.

Considering the extent and unusual lithological features of the sheared formations, it is surprising that so little mention of their occurrence has been made. Stirling (1884) in a note on the deposit suggested that the marmorisation was due to the quartz porphyry (rhyo-dacite) which he regarded as intrusive into the limestones. Howitt later discredited this view, and suggested that the changes in the limestones were due to the hydrostatic pressure exerted by an enormous thickness of overlying rocks. It is now apparent that a sufficient mass of rock could not overlie the limestones so as to marmorise one portion and yet leave the beds one hundred yards away almost unaffected. Whitelaw (1898) does not seem to have recognized the sheared easterly extension of the limestones, as his map shows the whole of this particular area as Upper Devonian conglomerate. The significance of a shear zone of such dimensions lies in the fact that its existence confirms, to some extent, the importance of faulting in the structural control of this particular portion of the Dividing Ranges.

Mt. Tambo Series.

The course of the investigation into the relations of the Bindi limestones provided some opportunities of examining the formation which constitutes Mount Tambo and the surrounding rugged country extending southward to Mount Waterson in the parish of Bindi. Two significant facts were specially noted in regard to the age of the Mount Tambo beds:

(1) In every case where the normal contact relationships between the Mount Tambo beds and the Middle Devonian limestones can be observed, it is found that the limestones are inclined in the same direction and to much the same extent as the Mount Tambo beds, and underlie the latter.

(2) Although the relationships in the north-east of the area are complicated by a shear zone due to faulting, the Middle Devonian limestones are separated from the typical Mount Tambo conglomerates by a zone of calcareous and siliceous conglomerates which may represent transitional deposits connecting the two formations.

A rather obscure exposure on the limestone-granite junction about $1\frac{1}{4}$ miles south of Bindi Creek shows coarse conglomerates between the two formations, dipping at a slightly higher angle than the limestones, but in the same direction. The rock is identical with the basal bed of the Mount Tambo series as described by Howitt (1876) and contains fragments of quartzite, quartz, and indurated slate.

The inference to be drawn from these statements is that, although the Mount Tambo series is on a higher horizon than the Middle Devonian limestones, the relationship between these two formations is in the nature of a disconformity, in contrast to the well-marked angular unconformity between the Middle Devonian Tabberabbera shales and the Upper Devonian Iguana Creek beds. Hence, assuming that the Middle Devonian beds of Bindi and Tabberabbera are contemporaneous, it seems that the Mount Tambo beds should be placed on a considerably lower horizon than the Iguana Creek beds. The matter cannot be decided on palaeontological grounds, since, although the Upper Devonian age of the Iguana Creek beds is suggested by the presence in them of the Cordaites-Archeopteris flora, no authenticated fossils have ever been recorded from the Mount Tambo beds. A single fish plate has been found on the top of Mount Tambo, but its affinities are not restricted to the Upper Devonian. Selwyn (1866) reported "plant-beds" at Mount Tambo, but no traces of any such have ever been subsequently found.

Much of the lithology of the Mount Tambo beds has been described by Howitt (1876) and Whitelaw (1898). However, an examination of the beds of this series exposed in the parish of Bindi showed two types not previously recorded: (1) sheared conglomerates; (2) arkoses. The rocks of the former group have already been noted as the Upper Devonian equivalents of the sheared limestones. Notwithstanding their hard and brittle nature, the quartz pebbles and grains of the Tambo beds have been distorted by the faulting into long needle-like splinters. The formation covers an area of a few square miles in the north-east of the parish, the resistant character of the rock giving rise to the precipitous heights of Mount Waterson. The arkoses form the massive sequence north-west of the Bindi limestones. The formation is remarkably uniform throughout the first 200 feet from the limestone contact, the general appearance being that of a yellowish grit, containing rare rounded quartz pebbles. The extent of this arkose has not been determined in the field.

Section No. 6012 shows the arkose to consist of rounded quartz grains set, with numerous felspar fragments, in a fine-grained siliceous ground-mass.

The edges of many of the quartz grains are not smooth, however, but show angular projections and embayments, suggesting that little transportation preceded sedimentation. The large angular fragments of felspar crystals also suggest rapid sedimentation at no great distance from the parent granite. The granitic rocks to the south of the outcrop are a possible source of the arkose components. However, the biotite, chlorite, and muscovite of the granitic rocks have not been found in the arkose. The quartz grains in the latter show intense internal strain effects, undulose and "shatter" extinction being much more prominent in these grains than in the quartz crystals of the granite (Plate 1, fig. 4).

Hypabyssal Intrusions.

Pegmatite.—Coarse tourmaline-bearing pegmatites, aplites and masses of graphic granite are common in the metamorphic "Omeo Schist" series in the south-east of the area. The dykes are similar in all respects to those commonly found throughout the whole of the north-eastern "Metamorphic Complex." One pegmatite vein occurs in the granitic rock in the south-west of the area.

Diabase.—A suite of decomposed basic dykes strikes north-west through the granite slightly to the north of Bindi Creek. The disturbed nature of the rocks in this region makes it impossible to trace the individual dykes for any appreciable distance, but all were found to end at the limestone contact. A well-exposed dyke in the bed of the Tambo River could be traced for 20 feet, but was then found to be cut off, presumably by faults. The dyke represents a fragment torn from a longer dyke by the faulting in the granite, there being many small fragments of similar dykes in the surrounding granite. These dyke fragments are almost indistinguishable from massive limestone in hand specimens. The dykes themselves are rarely more than 2 feet in thickness.

Monchiquite.—A peculiar type of basic dyke or dykes outcrops in the south-west portion of the limestones, immediately north of Limestone Creek. The accumulated thick soil on the hillside at this point obscures the shape of the outcrop as a whole, but fragments of the rock are exposed over an oval area of greatest length about 300 yards, suggesting a plug-like intrusion rather than a dyke. The surrounding rock is massive limestone, and fragments of it may be seen to be included in the basic dyke near the contact of the two rocks. The heat of the intrusion has only been sufficient to drive off the CO_2 of the limestone, leaving an impure yellow lime.

Petrographic Descriptions.

[Numbers in brackets refer to slides in the collection at the Department of Geology, Melbourne University.]

SILLIMANITE SCHIST.

The hand specimen is a greenish-brown fine-grained lustrous schist. It outcrops along Junction Creek to the east of the indurated Upper Ordovician-granite series. A large part of the section (No. 5991) is composed of sillimanite (fibrolite) in extremely fine felted fibres. A few shreds of reddish-brown biotite grade out into masses of fibrolite.

The large amount of sillimanite present—about 50 per cent. of the rock—in the complete absence of cordierite, pinite or andalusite, can conveniently be accounted for by assuming the metamorphic process to have been of a fairly intense thermal type, combined with a certain amount of orogenic pressure. The oriented structure of the schist, parallel layers of sillimanite alternating with chlorite-quartz layers, shows that stress conditions have been of importance during its formation.

All biotite has subsequently been chloritized, with the exception of isolated, red-brown shreds, occupying the centres of thick masses of fibrolite (Plate 1, fig. 3). Pleochroic haloes are frequent in the biotite and are represented in the chlorite by dark non-pleochroic stains. The haloes often surround recognizable zircons, which are plentiful in both schist and gneissic granite. Much of the fibrolite is intergrown with quartz, the needles of the former penetrating the edges of the quarz grains and giving them their serrated boundaries. Usually the central areas of the quartz grains are fairly free of included needles, but smaller grains are often split up into shred-like laminae, by bands of fibrous sillimanite. The simultaneous extinction of a number of these minute laminae over certain areas indicates the boundaries of the original grain. These grains are thus similar to the quartz sillimanitisé, as described by Barrow (1893), in which, however, sillimanite needles occupy the central portions of the quartz grains, leaving the edges of the latter relatively clear. A few crystals of orthoclase and oligoclase are scattered throughout the section. The similarity between the composition of the latter ($Ab_{72}An_{28}$) and that recorded by Tattam from many of the granitic and metamorphic rocks of the complex suggests that this felspar is magmatic in origin.

Gneissic Granite.

Section No. 5996 represents the outcrops to the west of the schist-granite contact on Junction Creek. Megascopically, the rock appears to be a moderately coarse-grained granite, showing fairly strong foliation, with parallel orientation of large elongated felspars. In thin section, however, the foliation is not so apparent. Large anhedral grains of normal granitic minerals—quartz, felspar, and biotite—are cemented together by a fine-grained matrix of quartz and sericite. The fine-grained quartz is obviously of metamorphic origin, having been deposited from solutions produced by local breakdown under pressure of the large primary quartz grains, resulting in the typically crenulate outlines shown by the latter. The whole is an early phase of true "mortar structure." Sericite, derived from the extensive decomposition of large areas of orthoclase and microcline-microperthite, is commonly intermingled with the siliceous matrix. A small amount of sericite is usually associated with crystals of oligoclase which are extensively fractured and kaolinized, with numerous embayments of clear secondary quartz, distinct from primary quartz, with its characteristic strings of minute inclusions.

Biotite is unaltered in the Junction Creek gneissic granite, but has been completely chloritized in the granitic rocks further to the north along the Tambo River. Well-defined rectangular patches of reddish biotite in minute flakes occur in Section 5996, and resemble the "knots" in schists described by Tattam (1929). Muscovite is ubiquitous throughout the gneissic rocks in the area. Small grains of zircon are common, and in Section 6001 large grains of apatite are gathered together with interstitial quartz, in a small segregation suggesting local concentration of mineralizers.

RHYODACITE.

A section (No. 5980) of the massive porphyritic rock forming the eastern bank of Old Paddock Creek contains phenocrysts of quartz, felspar, and altered ferromagnesian minerals, set in a fine-grained siliceous ground-mass containing much finely disseminated hematite. The quartz phenocrysts are embayed and devoid of inclusions. The felspar phenocrysts, approximately equal in number to the quartz, comprise plagioclase (sodic andesine $Ab_{35}An_{65}$) and orthoclase, and are extensively kaolinized. The plagioclase is approximately equal in amount to orthoclase. Phenocrysts of ferromagnesian minerals have been replaced by magnetite (now extensively oxidized to hematite), which frequently preserves forms characteristic of crystals of biotite, or, more rarely, pyroxene. Many of the magnetite clots have been drawn out along flow lines, resulting in the high concentration of hematite dispersed throughout the ground-mass, the hypocrystalline texture of which suggests devitrified glass.

An unusual feature is the association of minute crystals of hypersthene with a particularly large area of hematite. The intensity of the pleochroism and the low optic angle (about $30°$–$40°$) indicate a variety rich in iron. The concentration of the hypersthene crystals along the margins of the hematite clot suggests that they have originated by reaction of the siliceous ground-mass with the magnetite. The sequence of reactions during the formation of the rock would thus include recrystallization of biotite prior to extrusion, then, on extrusion, break-down of the biotite to magnetite, and, finally, reaction of the magnetite with the remaining liquid to give small quantities of hypersthene.

TUFFACEOUS RHYODACITE.

Section No. 5997 represents the rock from the south-western limit of the lava flows. It is similar to the massive lava, but contains in addition numerous embayed fragments of quartz surrounded by thick mantles of minute, interlocking, quartz crystals.

DYKES.

(*a*) *Diabase*.—Section (5979) is taken from the dyke (D.4) exposed in the bed of the Tambo River. The rock is fine-grained, of trachytic texture, composed of laths of felspar and a ferro-magnesian mineral now so decomposed as to be indeterminate. The only other recognizable minerals are secondary calcite and sericite. The rock is conveniently described as "diabase" because of its appearance in the hand specimen and advanced alteration.

(*b*) *Diabase: (Chilled Margin)*.—Section (5981) shows the contact of one of the diabases exposed on Cairn Hill, with the surrounding granite. A distinct border phase about 5 mm. in width extends in from the contact, which is sharply defined. Large crystals of augite, now extensively altered to serpentine, are set in a dark, fine-grained ground-mass, just inside the contact. These phenocrysts do not occur in the portions of the dyke away from the contact.

(*c*) *Monchiquite*.—This rock, which forms the basic plug near Limestone Creek, varies in appearance from a dense, black, glassy material, to a red-brown mass set with numerous black phenocrysts of hornblende, ranging up to an inch in length. Sections (Nos. 5983–5989) show that the texture varies from basaltic, with numerous small phenocrysts, to porphyritic, with a hypocrystalline ground-mass. The porphyritic variety appears to represent a chilled border phase, and often contains fragments of indurated limestone.

The sections show a variety of stages of resorption of hornblende, which is of the oxy-hornblende type, pleochroic from yellow to dark red-brown. During resorption, magnetite dust and pyroxene (titanaugite) are formed, the magnetite gradually extending throughout the body of the phenocrysts (Plate 1, fig. 2). Depending on the relative movement between the phenocryst and ground-mass, the pyroxene is either swept away as it produced or deposited as a shell around the parent hornblende. A striking instance of this latter formation is shown in Section 5985 (Plate 1, fig. 1), where the parent hornblende has formed an optically continuous shell of pyroxene and magnetite around itself, thus shielding the inner hornblende from contact with the ground-mass. At a later stage, this shell has been breached, allowing the ground-mass to pour in. In all instances where pyroxene has crystallized round hornblende, the "C" axes of the pyroxene shell, and the inner hornblende fragments, coincide. The extinction positions of the shell and core are thus separated by an angle of about 30°–40°. A similar series of resorption stages is described by Larsen (1937) in the hornblendes of the Colorado andesites. The evidence in these lavas suggested that concentration of mineralizers rather than pressure conditions is the determining factor in the amphibole-pyroxene equilibrium. Thus as the mineralizing vapours escape on extrusion, the hornblende becomes unstable and breaks down to pyroxene. In the case of the small hypabyssal intrusion at Bindi, most of the resorption must have occurred before final intrusion as a dyke or plug, i.e., loss of mineralizers must have occurred while the magma was contained in a subterranean chamber large enough to maintain a high temperature for a period of time sufficient for most of the resorption to take place. Numerous small olivines are present in all sections, rarely attaining large dimensions, and usually much altered to serpentine. The ground-mass is composed of small laths of oxy-hornblende and titanaugite set in a glassy base containing rare minute felspars. A few of the larger pyroxene laths have a green central zone, which may be soda-augite.

Marmorized Limestone.

Section No. 6011 represents the fine-grained pinkish "marble" outcropping in the centre of the shear zone near the locality commonly known as "Marble Gully." The rock here represents a fossiliferous limestone which has been subjected to intense shear, so that most of the original structure has been obliterated.

Microscopically, the rock is composed of minute grains of calcite, interlaminated with carbonaceous material and hematite. The minute size of the individual calcite grains renders their examination difficult, but their appearance in elongated masses, which "tail off" into the surrounding matrix, suggests considerable intergranular movement under conditions of shearing stress, rather than recrystallization under pressure.

Section No. 5982 is taken from a calcareous conglomerate outcropping a short distance north-west of the locality of Section 6011. The slide contains a pebble of massive blue limestone about 1 inch in length, which shows a moderate amount of recrystallization, and considerable elongation with development of tension gashes and slip planes. Two distinct groups of shear surfaces can be observed.

(1) The trace of the (ab) plane of the tectonite is not well defined in this particular section, but, as far as can be determined, it makes a slight angle with the axis of elongation of the pebble as a whole. The

actual elongation of the pebble has thus been produced by a mechanism distinct from that of direct rupture, which, although it is responsible for the S surfaces of Group (1), has produced only a subsidiary distortion of the pebble.

(2) The main process which has caused the elongation of this particular pebble has been gliding along the slip planes of the individual calcite crystals. The minutely displaced lamellae are everywhere well defined, and show a decided statistical preference for one particular plane in the fabric. Sander (1930) has shown that all such lamellae boundaries in deformed calcite grains are crystallographic "e" planes (0112). Although it can be stated that the rock is a tectonite which shows little mimetic recrystallization, the evidence for translation along the single slip-plane mentioned above is not reliable enough, when taken from a section on an ordinary microscope, to show that the fabric has not been produced by B-rotation. Thus, it is still possible that a universal stage determination would show a series of intersecting slip planes all parallel to a well-defined "B" axis.

Tension gashes, although normal to the axis of elongation, have been filled with crystals of secondary quartz which show parallel alignment along a direction which makes an angle of 20°–30° with the axis of elongation, i.e., the crystals are arranged "en echelon" in each tension gash. It seems necessary, therefore, to recognize two distinct phases of tectonic activity, the first of which produced the tension gashes during elongation of the pebble, whilst the second gave rise to the orientation of the quartz crystals. The undulose, sub-parallel extinction of the quartz suggests that pressure operated after, as well as during, the growth of the crystals.

Age Relations and Tectonics.

Upper Ordovician.—At Bindi, rocks of this age comprise both contact and regionally metamorphosed types. Both types are, as far as is known, contemporaneous, and are distinguished by the degree of alteration. The fact that both are represented in the limited area of the parish of Bindi is probably due to extensive faulting along a line striking N.N.W. through this area.

(?) *Siluro-Ordovician.*—The granites which have intruded and altered the Upper Ordovician sediments are provisionally classed here. They have been tentatively classed as Lower Devonian by previous workers (Skeats, 1931). However, their relations with the overlying Middle Devonian rocks at Bindi show that the contact is in the nature of an enormous unconformity, the extent of which can be assessed from the following evidence:—

(1) The metamorphic basement complex comprises intensely folded schists and gneisses, whilst the overlying formations are relatively flat-lying lavas and Middle Devonian limestones.

(2) The mineral content of the sillimanite-garnet schists and gneisses indicates that they were formed under conditions of temperature and pressure such as would exist near the intruding granites, in a geosyncline during orogenesis. A considerable period of time would be required for the removal of the upper levels of the folded geosyncline before the flat-lying limestones could be deposited. The interval between Lower and Middle Devonian seems inadequate.

Lower Devonian.—Lavas and tuffaceous extrusives underlying the Middle Devonian limestones in the north-eastern districts of Bindi are provisionally grouped as Lower Devonian. They are identical with the massive varieties among the Snowy River "porphyrites" underlying the Buchan limestones. Howitt (1878) has shown that these latter flows are conformable to the Middle Devonian, grading upwards through calcareous breccias and tuffs into normal limestones, so that their age may possibly be early Middle Devonian. Evidence relating to this point has been collected and correlated by Professor E. W. Skeats (1909, p. 182).

Middle Devonian.—The Bindi limestones are placed here on palaeontological evidence. They show some faunal differences from the Lower Devonian (?) Lilydale limestones, but show similarities with the Buchan and Tabberabbera beds. The Mount Tambo beds may belong here, as no marked unconformity is apparent between their basal members and the top of the limestone series.

Upper Devonian.—The Mount Tambo series is provisionally allotted to an early Upper Devonian age. The fact that this series has been involved with the Middle Devonian in an orogeny which is possibly connected with orogenic activity in Central Victoria towards the close of the Devonian, suggests that the Tambo beds are older, and the Iguana Creek beds are younger, than this orogenic period. This assumes that the diastrophism affecting the Tambo beds was not of local character.

Post-Upper Devonian.—The monchiquite penetrating the limestones is placed here. The rock resembles the Tertiary dykes in other parts of the State. Rock sections in the Howitt collection show that an exactly similar type occurs at Back Creek, Buchan, though its stratigraphical relations have not been observed by the author.

The evidence to be found at Bindi is not complete enough in itself to allow a definite decision to be made regarding the course of events in the tectonic history of the area. A detailed survey of the districts to the south and north-west would have to be made before any suggested sequence of events could be regardeed as proved. However, the following observations have suggested the sequence that will be given below:—

(1) There is a considerable difference in constitution between the rocks forming the western side of the igneous-metamorphic basement and those forming the eastern side of the area. No transition phases could be found on an east-west traverse along Junction Creek. By analogy with the similar petrographic break which occurs along the Tongio Gap fault (about 10 miles west of Bindi), it is suggested that the abrupt junction in the basement complex has been brought about by extensive movement along a pre-Middle Devonian fault.

(2) The limestones dip west at an average angle of 30 degrees, as far as the granite boundary. Since the contact here is not intrusive, and the dips at the contact increase to 60°–70°, the only possible explanation is that of a fault junction. This contact can be observed in a cliff section in the Tambo valley, and suggests that the granitic rocks have been thrust over the limestones. Mineralized quartz veins are prominent along this fault junction and slickensided surfaces are common in the nearby granite.

(3) In the marmorized zone in the north-east of the parish of Bindi, the extent and intensity of the deformation provide confirmatory evidence of the importance of fault action in the tectonic history of the area. The faults in this zone are not sharply defined, but are probably of the same nature as the thrust fault in the west of the parish.

From the above points, the following sequence is suggested:

(i) Pre-Devonian faulting, which is required to bring the highly metamorphosed Omeo series into contact with little altered sediments which are, as far as is known, contemporaneous. Subsequent deposition of the Devonian limestones and conglomerates, coupled with later thrust faulting along the line of the pre-Devonian fault, has obscured the actual position of the latter.

(ii) The extrusion of the acid lavas and the deposition of the limestones and conglomerates was followed (probably at the close of the Devonian) by an era of strong compressive forces directed along an east-west line. The granitic rocks in the basement complex of eastern Victoria yielded to this compression by breaking up along thrust planes into crystalline wedges. The overlying Devonian sediments were folded to an extent depending on their distance from the orogenic regions of Central Victoria. Thus, at Tabberabbera, the folding of the Middle Devonian rocks is acute, whilst at Buchan, further east, it is much less intense. At Bindi, only a thin lava flow separates the Middle Devonian limestones from the crystalline basement. Thus, movement along thrust faults in the basement rocks has brought portion of the basement complex above the level of the limestones. The western extension of the limestones has been sharply cut off, whilst their eastern extension has been drawn out in a shear zone some three miles in width. Conglomerates of the Mt. Tambo series have also been involved in this shear zone, whilst some of the western members of the series have been forced upwards by the granitic wedge, great masses of quartzites and contorted phyllites being developed along the contact of the wedge with the overlying conglomerates.

Summary.

The basement rocks at Bindi comprise types characteristic of the metamorphic complex of north-east Victoria. They are unconformably overlain by acid lavas which form part of the Snowy River Volcanic Series. The extreme nature of the unconformity suggests that the Lower Devonian age previously given for the granites of the metamorphic complex should be reconsidered. Middle Devonian limestones conformably overlie the acid lavas and tuffs. Their lithological, palaeontological, and structural characteristics are described. The Mount Tambo series, comprising conglomerates, sandstones and arkoses, overlies the Middle Devonian limestones, with little or no angular unconformity. Both the Mount Tambo series and the Bindi limestones have been involved in a series of thrust faults, developed in the underlying crystalline rocks. The sedimentary series owe their

preservation and present attitudes to this thrust faulting. An extensive zone of intense rock deformation occurs in the east of the area, and is shown to be due to fault movement.

In conclusion, I would like to acknowledge my indebtedness to Professor H. S. Summers and the staff of the Geology School for their ready advice and assistance during the progress of this investigation; to the various students of geology, whose companionship made field investigations in little-known and rather inhospitable country not only possible but enjoyable; and to Associate-Professor E. S. Hills especially, for his invaluable discussion and criticism of the ideas expressed in this paper.

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Description of Plate.

FIG. 1.—Monchiquite. Bindi. Basal section of augite-magnetite shell during resorption of oxy-hornblende phenocryst.

FIG. 2.—Monchiquite. Bindi. Early and late stages in the resorption of oxyhornblende phenocrysts. The left-hand phenocryst has been almost completely replaced by magnetite and augite.

FIG. 3.—Sillimanite Schist. Junction Creek. Bindi. Contorted mass of fibrolite needles, surrounding shreds of a mineral resembling biotite.

FIG. 4.—Arkose. Bindi. A rounded quartz grain appears in the lower right-hand corner. The matrix is composed of fragmentary quartz, plagioclase and orthoclase.

FIG. 5.—Marmorized limestone from shear zone. Bindi. The black streaks represent traces of shear planes.

FIG. 6.—Normal limestone. Bindi.


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